Review of Micro-Propulsion Ablative Devices

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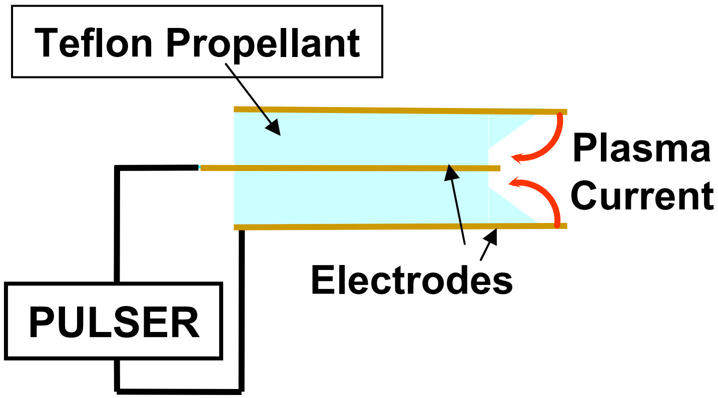
Outline

- Examples of micro propulsion ablative devices
- Fundamentals of ablation
- Detailed analysis of specific devices
  - Micro-Pulsed Plasma Thruster
  - Micro-Laser Plasma Thruster
  - Micro-Vacuum Arc Thruster
- Summary and Future Needs

Micro-Pulsed Plasma Thruster (AFRL)

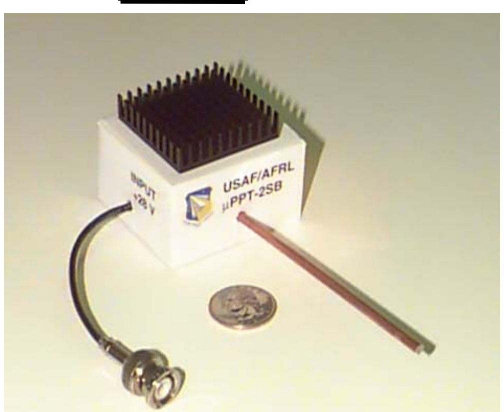


100 grams

Energy	1-10 J
Thrust-to-Power	1-10 μN/W

Simple Engineering

Ablation rate:
10 cm in 100 hour, 1 Hz



Triggerless ignition

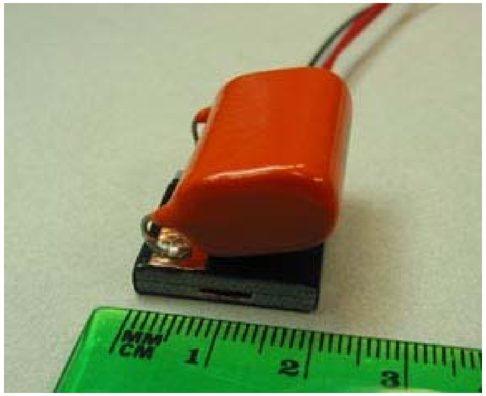
FalconSat

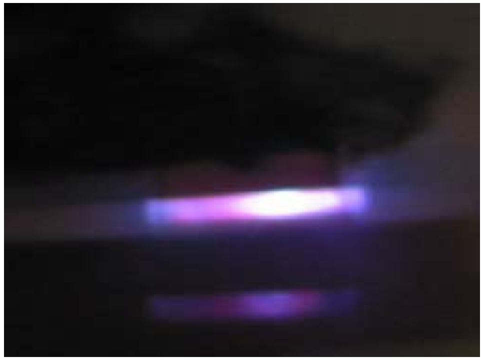
US Air Force Academy, 2005
<100-kg class

MicroPPTs

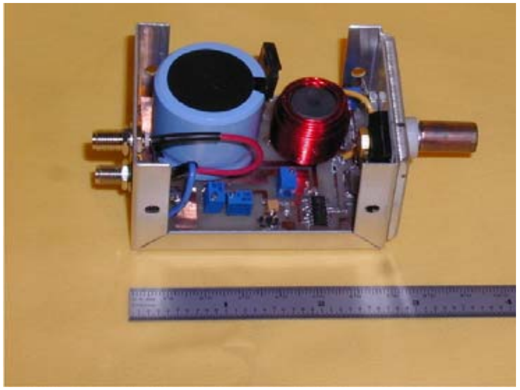
Micro-PPT Technology Development (JHU-APL)

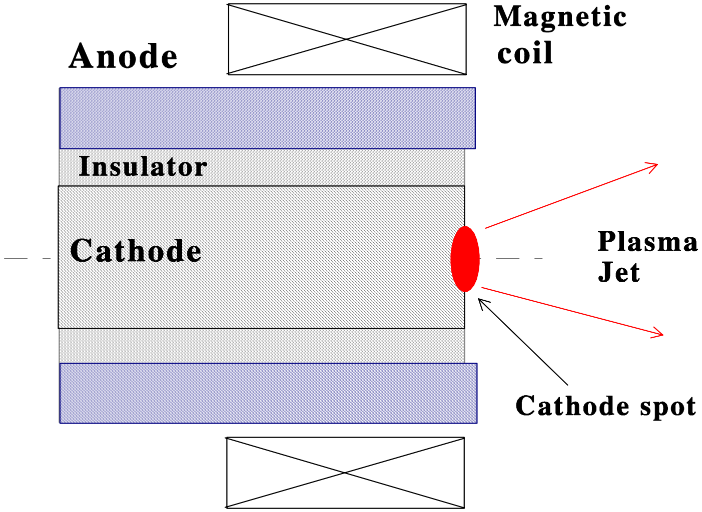
- APL exploring fundamental effects associated with device scaling
- Examining influence of energy deposition and electrode geometry upon electro-mechanical response
- Developing novel techniques for micro-PPT device characterization





Micro-Vacuum Arc Thruster (AASC)

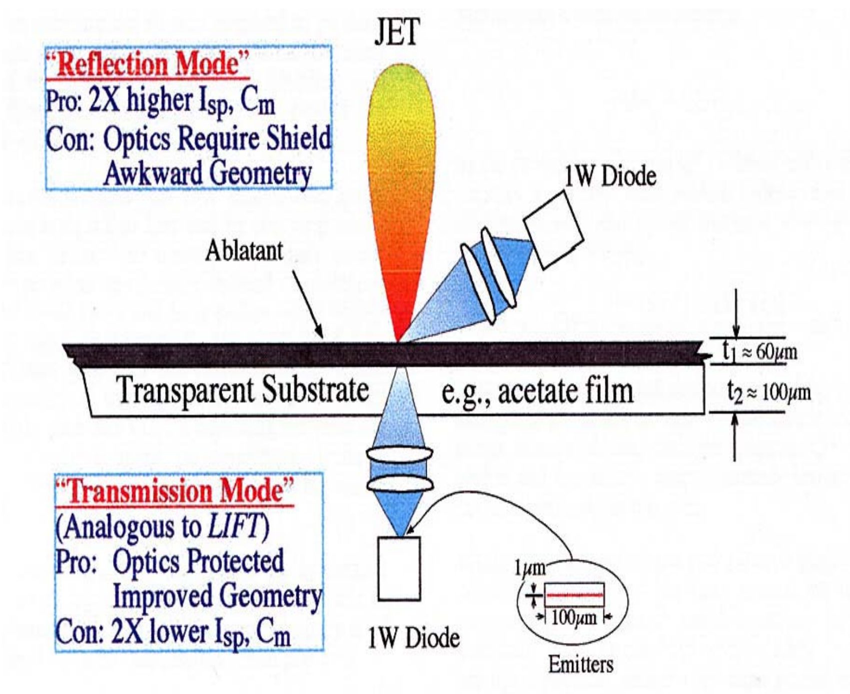


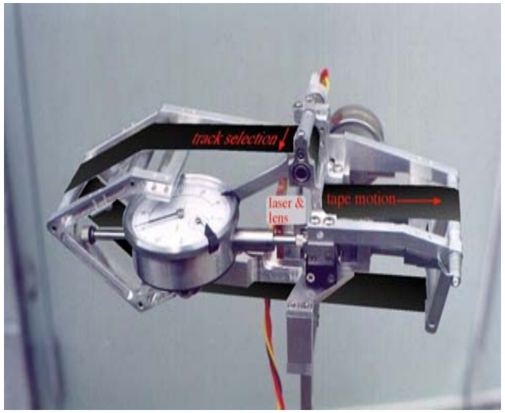


Inductive energy storage PPU (efficiency of the PPU >90%)
Low mass (<300g)
Typical current ~100 A
Voltages of ~25-30 V.
Total efficiency ~10%
I_{sp}~1000-3000 s
T/P~10 μN/W

Micro-Laser Plasma Thruster

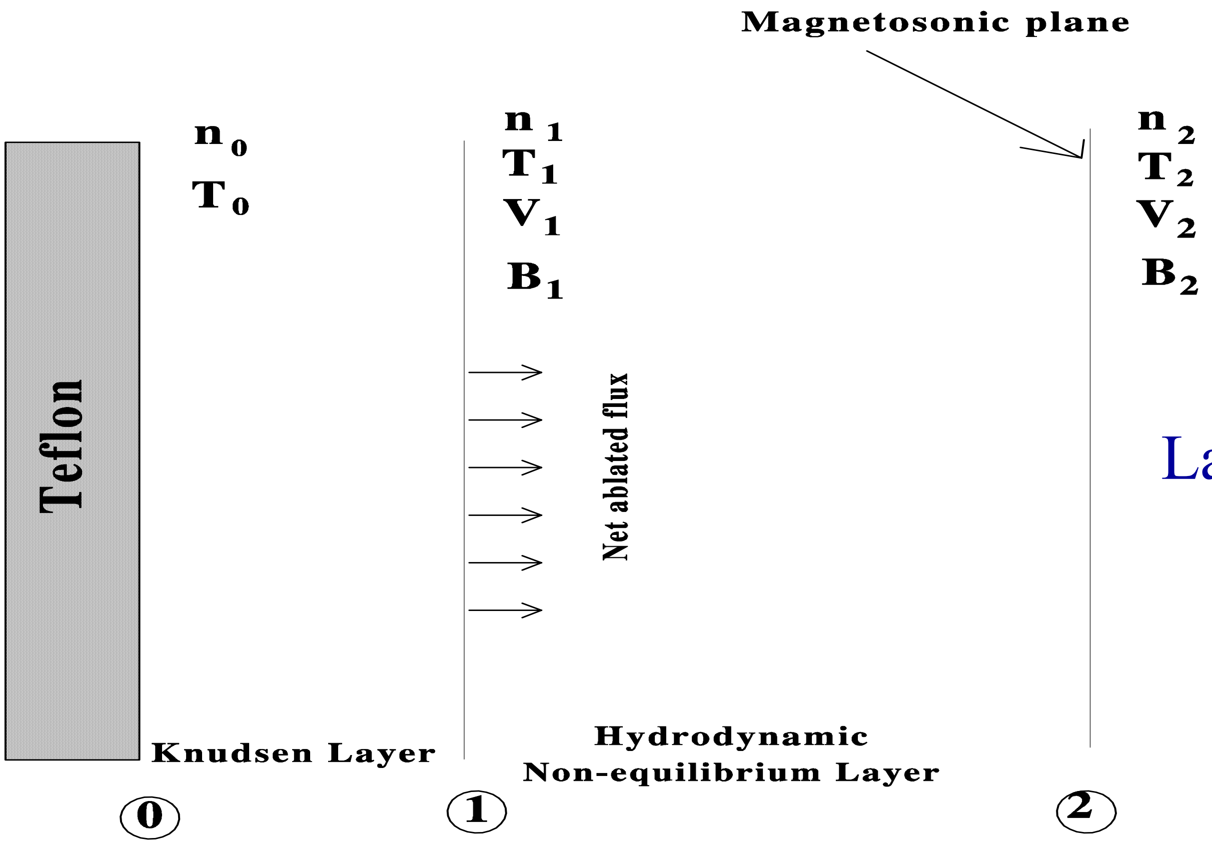
•micro Laser-ablation Plasma Thruster, μ -LPT (Photonics Associates).
-micro chip Laser-ablation Plasma Thruster, (Lincoln Lab).





Power: 2-14 W
Pulse duration: 3-10 ms
Q^*: $2x10^7$ J/kg
C_W: 60-100 μN/W
I_{sp}: 300-1000 s

Ablation Fundamentals



Layer structure near ablated surface

Kinetic model of the Knudsen Layer (1)

Analytical and particle (DSMC) approaches:

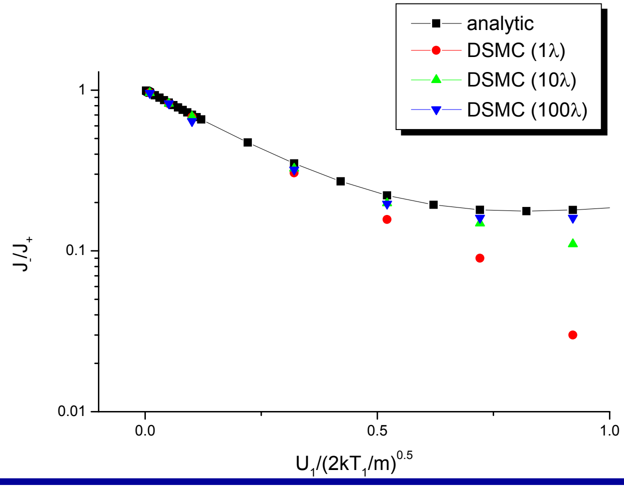
$\int V_x f(V)\, dV = \text{const}$ (mass)

$\int V_x^2 f(V) dV = \text{const}$ (momentum)

$\int V_x V^2\, f(V) dV = \text{const}$ (energy)

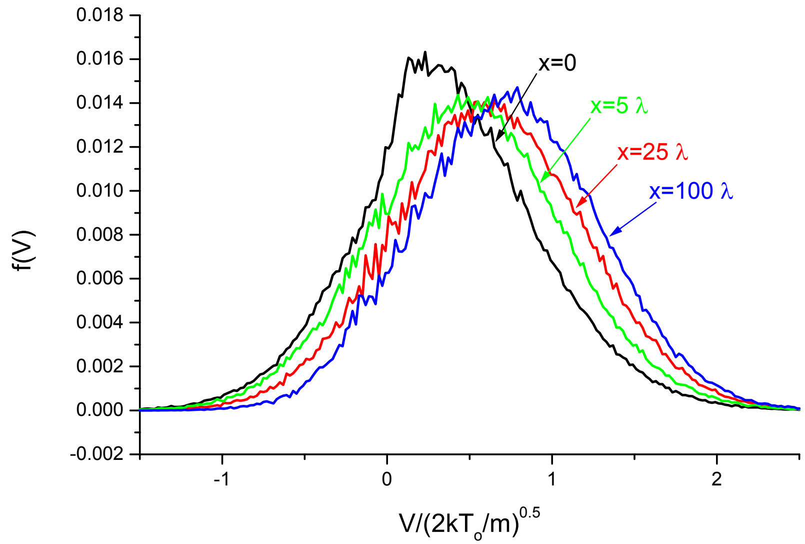
$f(x,\mathbf{V}) = \xi(x) f_1(\mathbf{V}) + (1 - \xi(x)) f_2(\mathbf{V})$
where $\xi(x=0)=1$ and $\xi(L)=0$ with $x=0$
[Mott-Smith, 1951]

$f_1(\mathbf{V}) = n_o \beta^{3/2} \exp(-V^2)$ $V_x>0$
$f_1(\mathbf{V}) = \delta f_2(\mathbf{V})$ $V_x<0$
$f_2(\mathbf{V}) = n_1 \beta^{3/2} \exp(-(v-U)^2)$
[Anisimov, 1968]

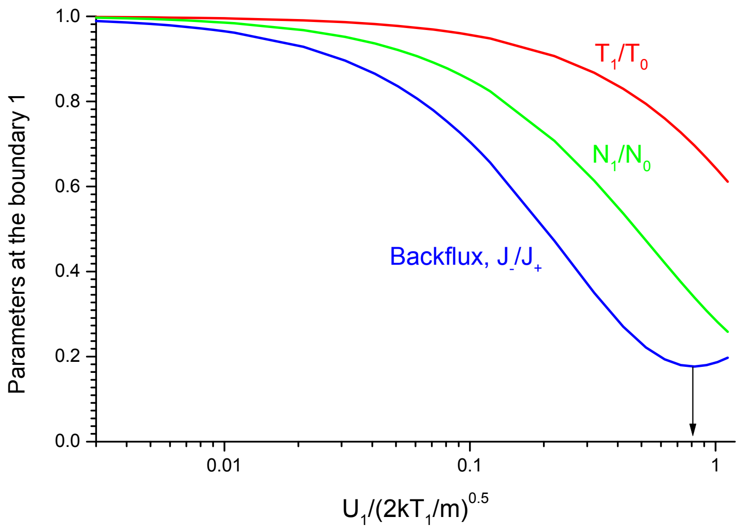


Kinetic model of the Knudsen Layer (2)

Particle distribution function. DSMC



Parameters at the Knudsen layer edge



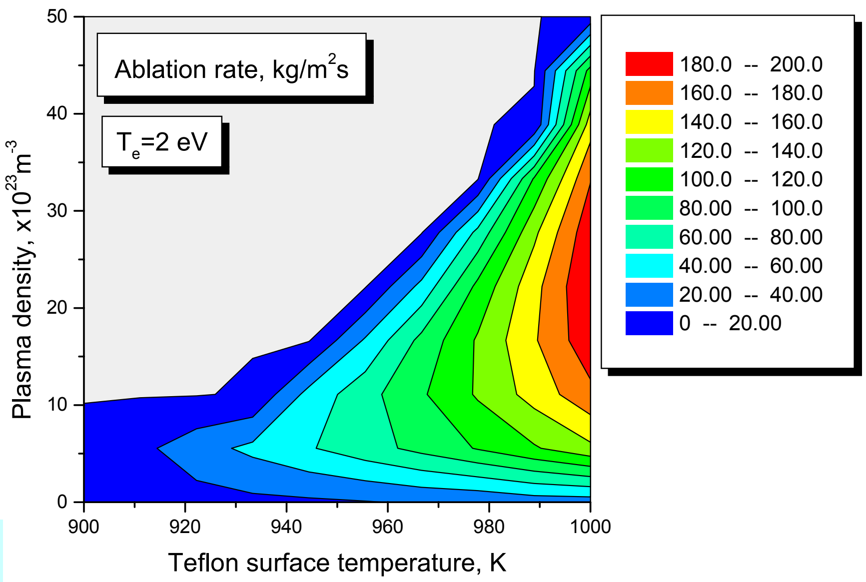
Hydrodynamic Layer

$$d(nV) = 0$$

$$M(nV)\frac{dV}{dx} = -\frac{d(nkT)}{dx} + j \times B$$

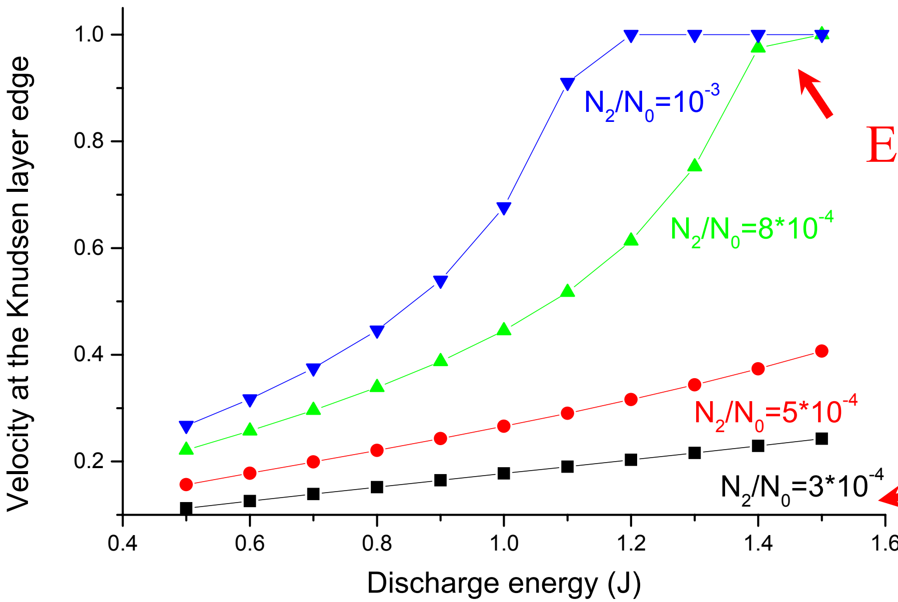
$$\frac{MV_1^2}{2kT_1} = \frac{\dfrac{n_1}{2} - \dfrac{T_2 n_2}{2T_1} + \dfrac{1}{4}\cdot\dfrac{\mu(jd)^2}{kT_1}}{\dfrac{3}{2}\cdot\dfrac{n_1^2}{n_2} - n_1}$$

Example: electrothermal thruster



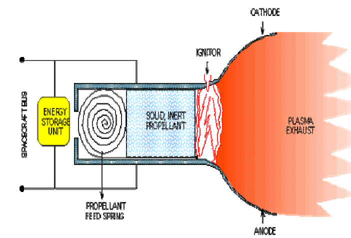
V_1 depends on the specifics of acceleration (n_2, j)

Velocity at the Knudsen Layer Edge



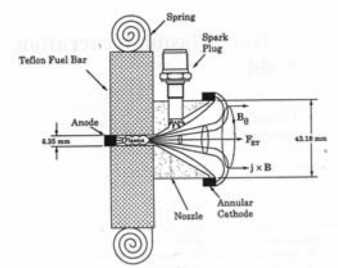
(Current density)

Electromagnetic PPT



Mikellides *et al*

Electrothermal PPT

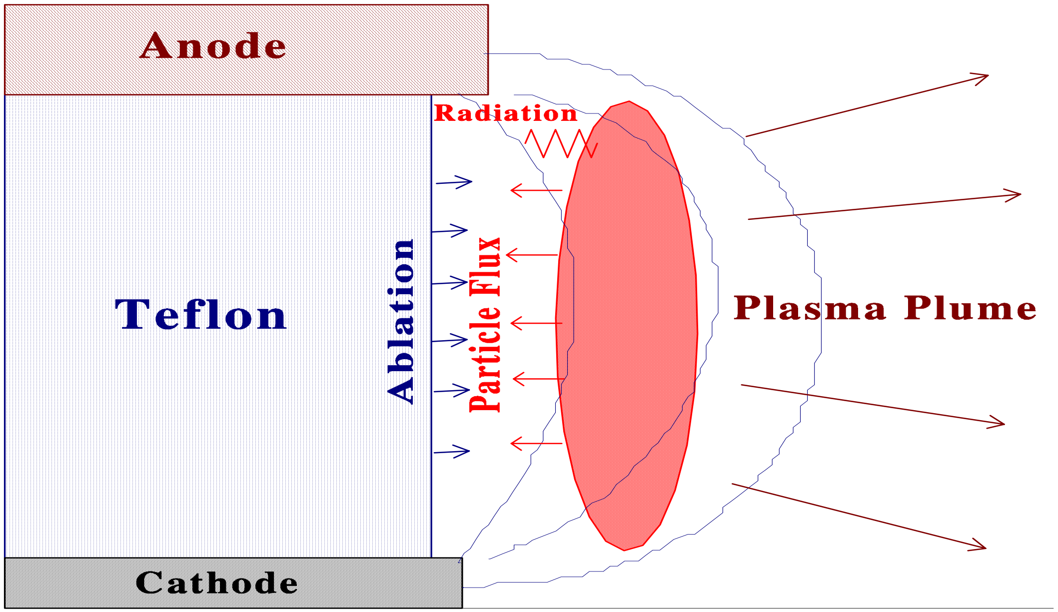


Keidar *et al 2000*

Electromagnetic acceleration leads to transition to vacuum evaporation regime

In addition to acceleration mechanism PPTs can be classified by ablation mode

End-to-end simulation



ablation

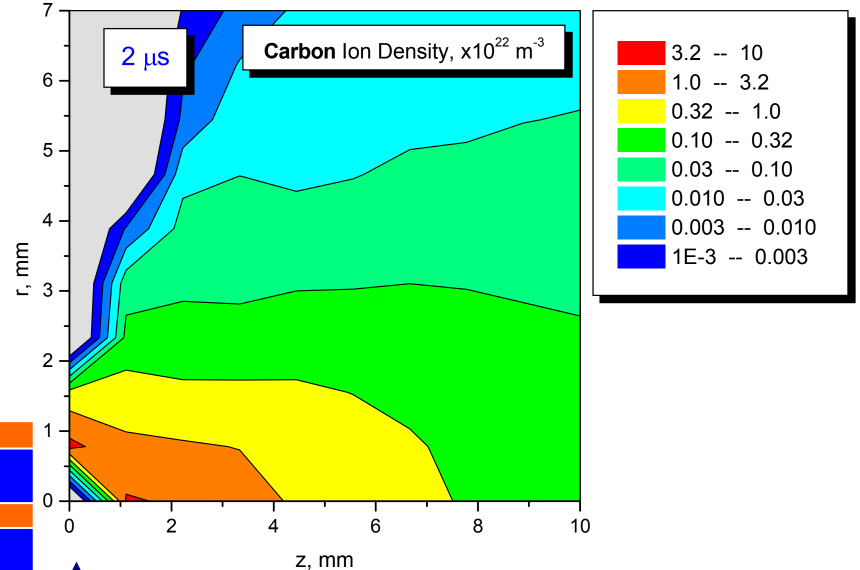
ionization

Plume expansion

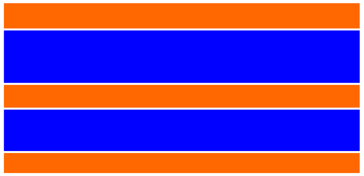
Magnetic diffusion

Fluid Particle

Comparison with experiment (1)



1/4" DIA μ-PPT, 6 J



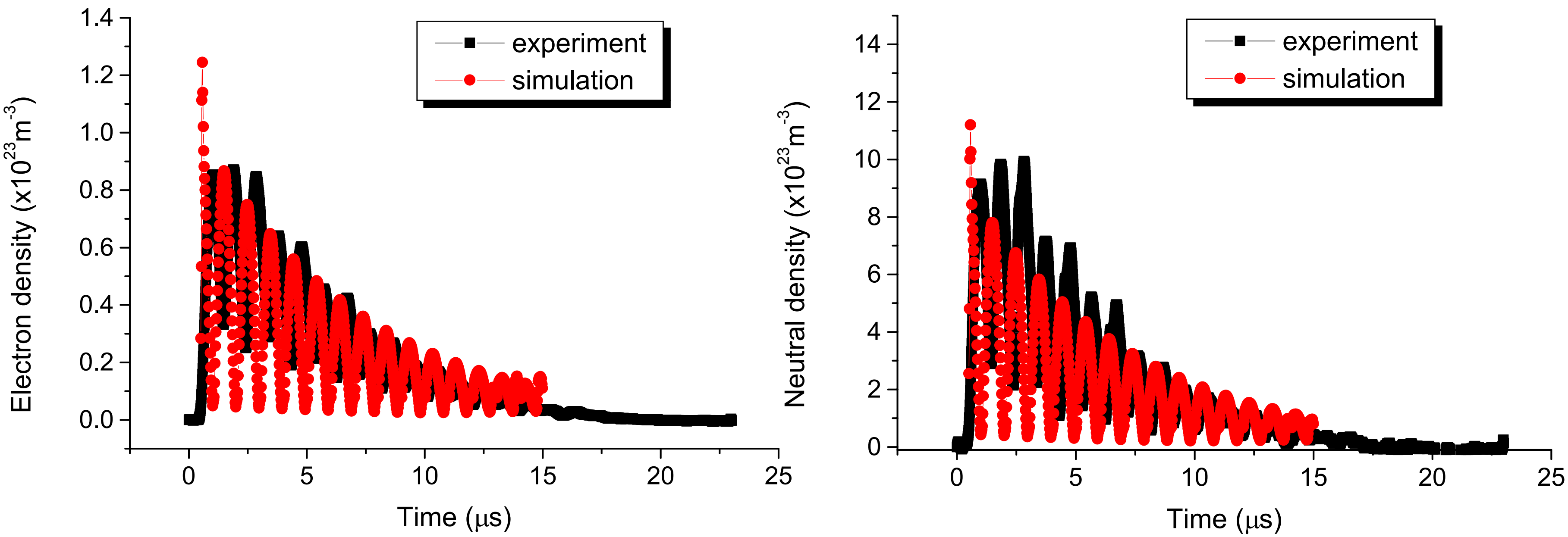
6 mm beam width

3 mm

Herriot Cell interferometer
Antonsen, Burton & Spanjers, IEPC-01-157
Antonsen, MS Thesis, UIUC 2001

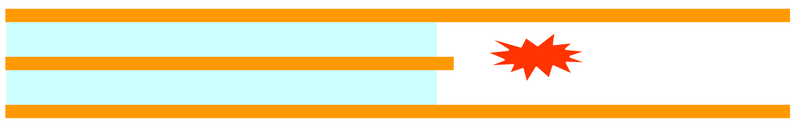
Comparison with experiment (2)

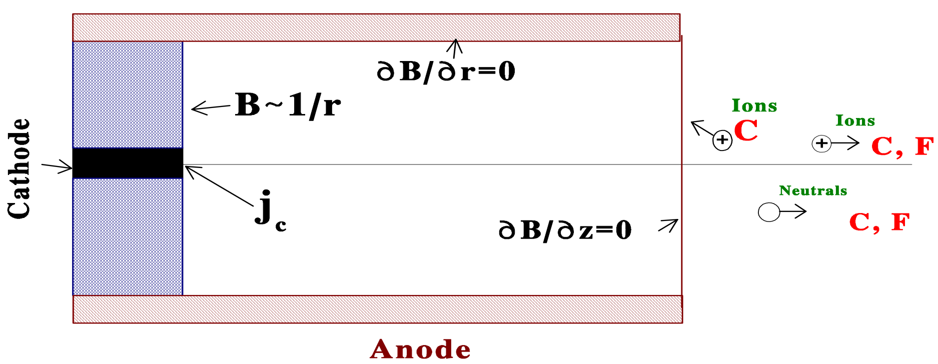
1/4” DIA μ-PPT, 6 J



Self-consistent non-equilibrium ionization model

Propellant recession (1)



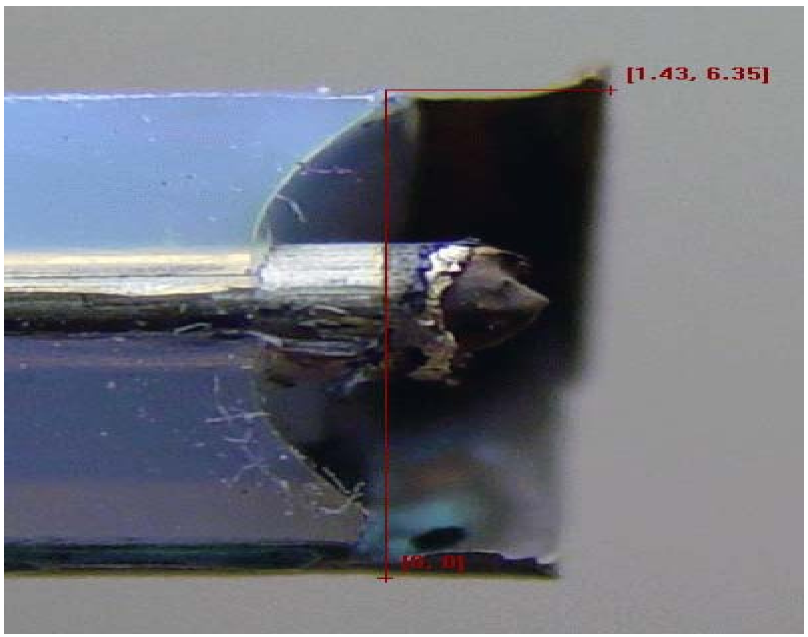


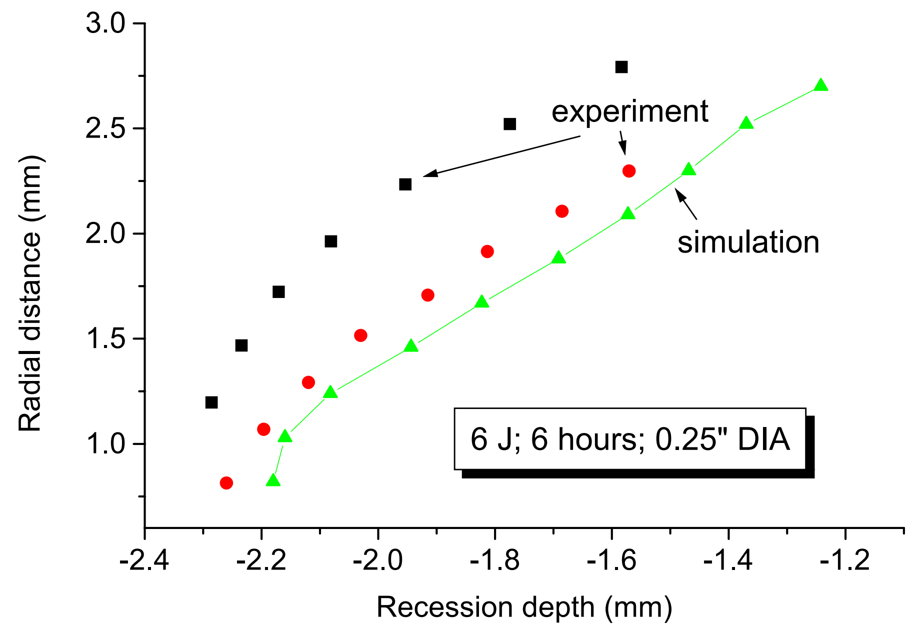
- 2D PIC-DSMC model & magnetic transport
  - time-dependent boundary conditions plasma layer model
  - magnetic field & current distribution (energy balance & ion dynamics)
  - collisions (elastic & non-elastic)

Propellant recession (2)

1/4” DIA, 6 J

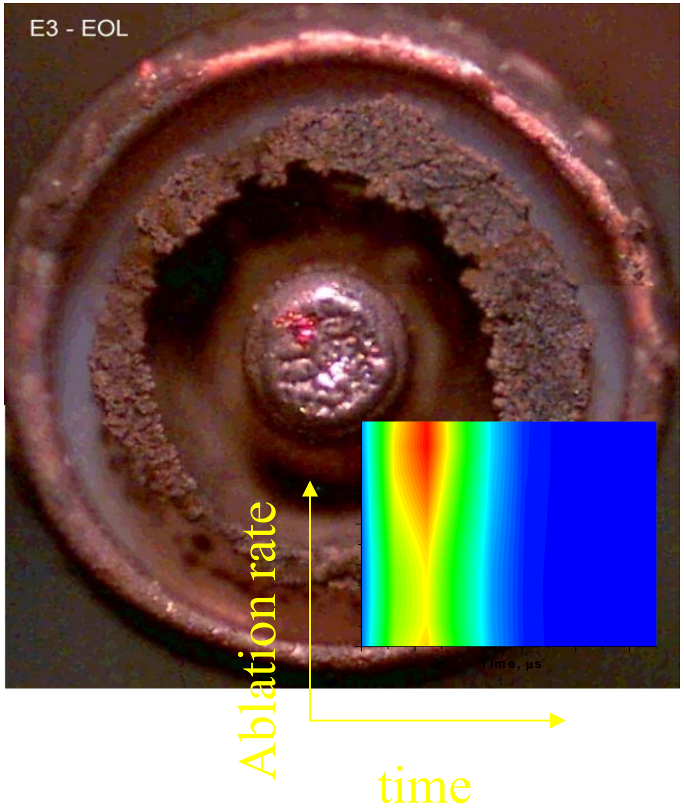
6 hours, 1Hz





Ablation pattern: Charring

Ablation rate calculations are based on plasma layer model and ablation theory



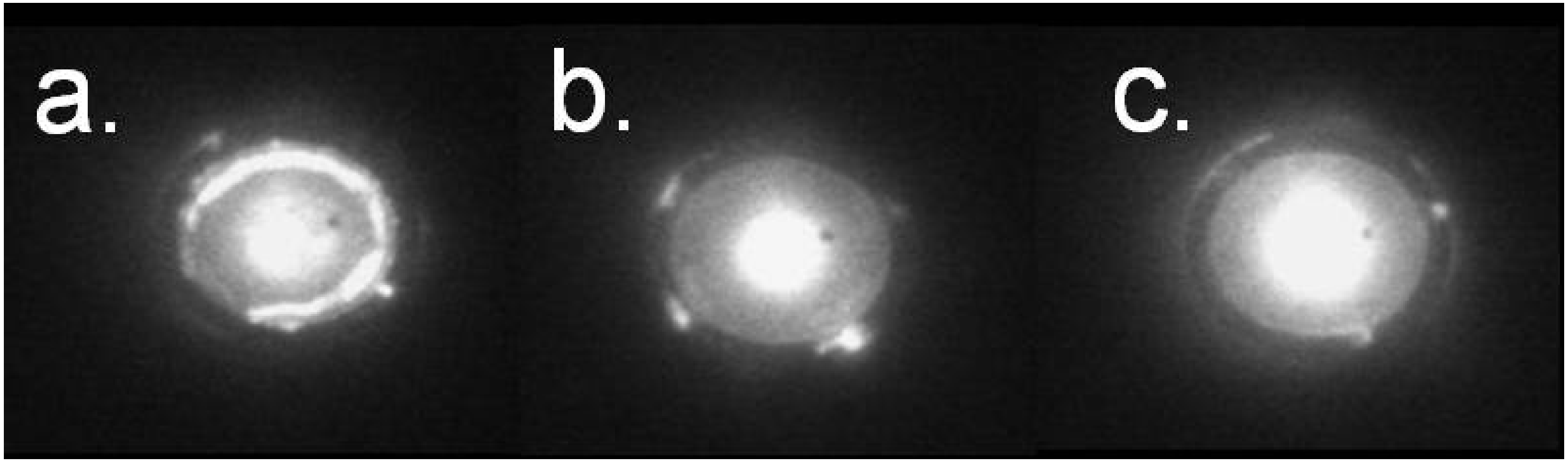
<u>AFRL Experiment</u>:

Tests agree with model – Cold thrusters char easier

Discharge non-uniformity

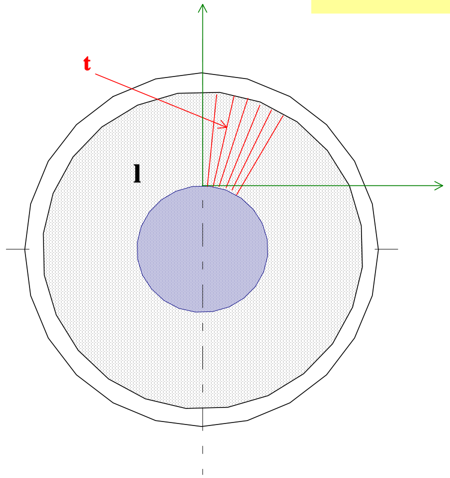
High speed camera
visible emission

Arc spoking increases with energy

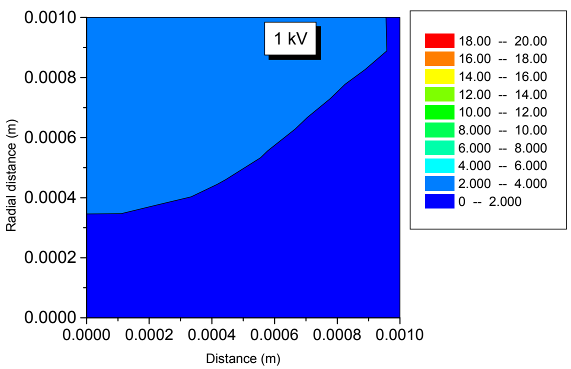


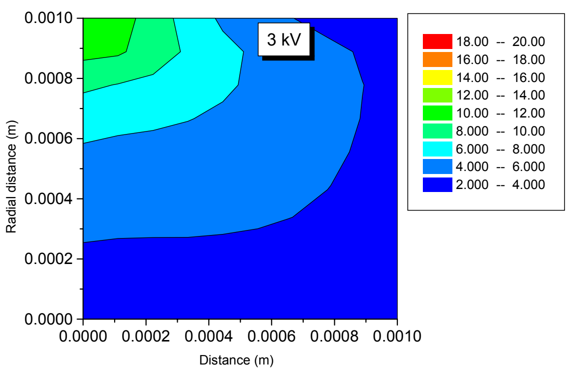
2.30 J 5.55 J 6.73 J

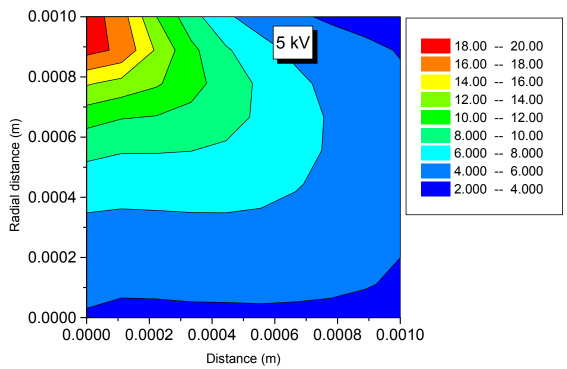
Current constriction modeling



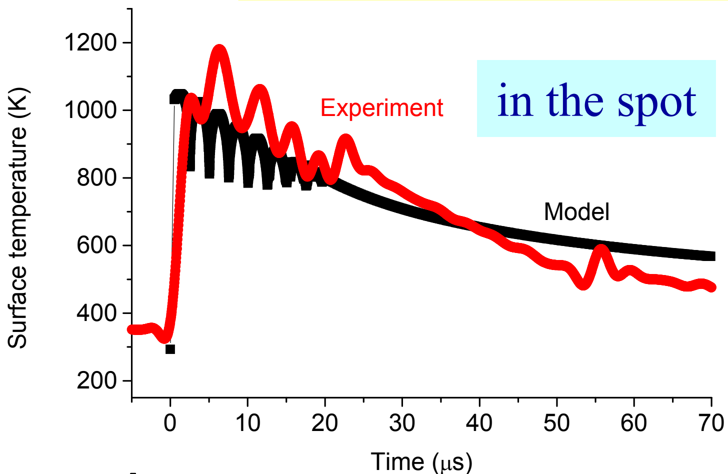
Two-fluid MHD
Calculated current density
(normalized)

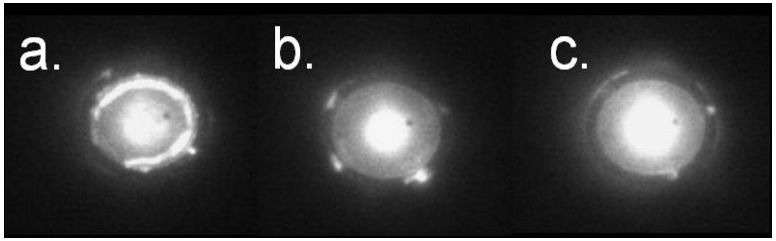


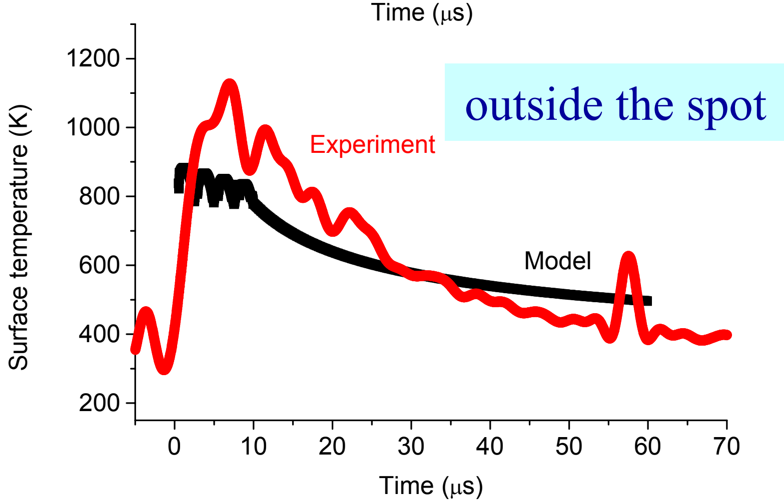


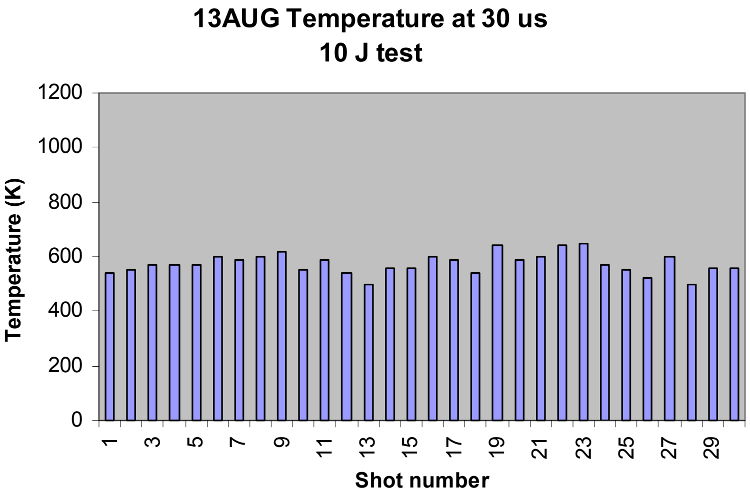


Surface temperature (1)

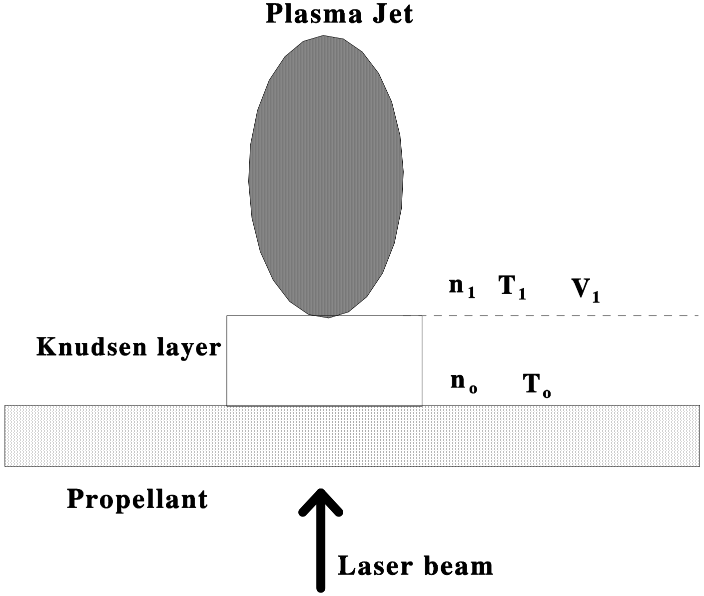








Micro-Laser Plasma Thruster



- Energy equations:

$$\frac{3}{2} n_e V \partial T_p / \partial x = Q_{IB} - Q_{ei} - Q_\lambda$$

- Dominated by inverse-Bremsstrahlung

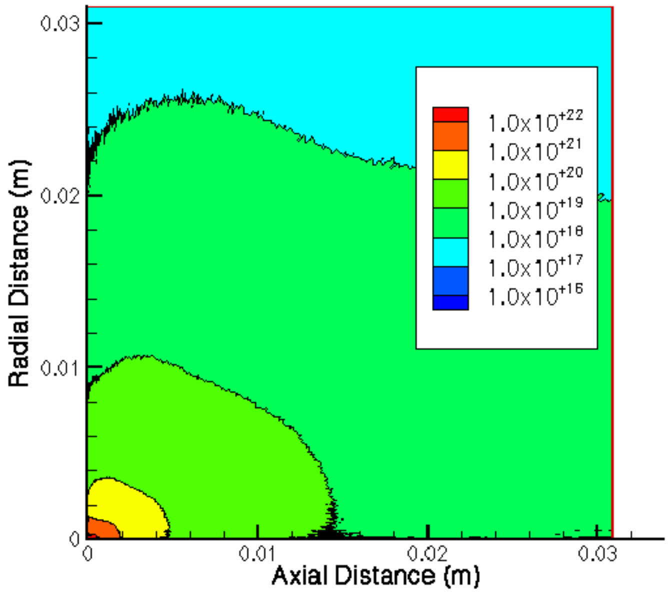
$$Q_{IB} = \alpha_{IB} I_0 \exp(-\alpha_{IB} x)$$

$$\alpha_{IB} = 1.37x10^{-35} \lambda^3 N_e^2 T_e^{-\frac{1}{2}}$$

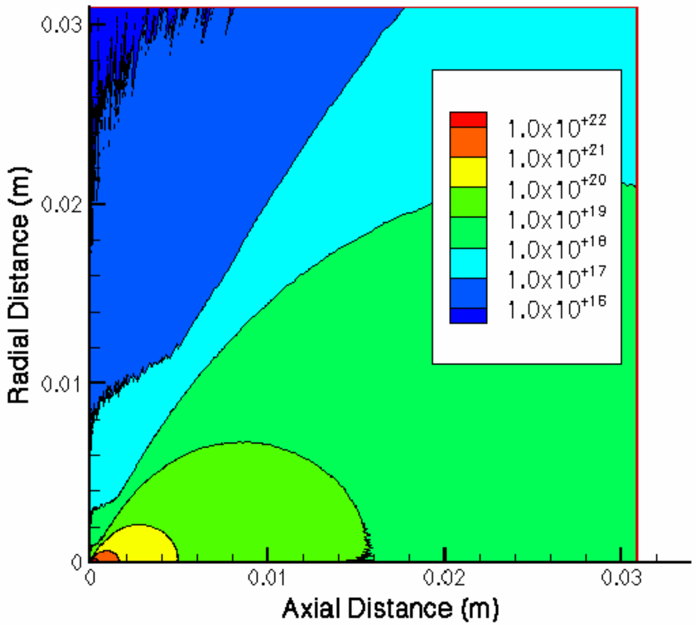
- Plasma properties:
  - composition (C,H,C^+,H^+, Cl)
  - assuming LTE

Plume Simulation (PIC-DSMC)

P=6.5x10^{-5} torr



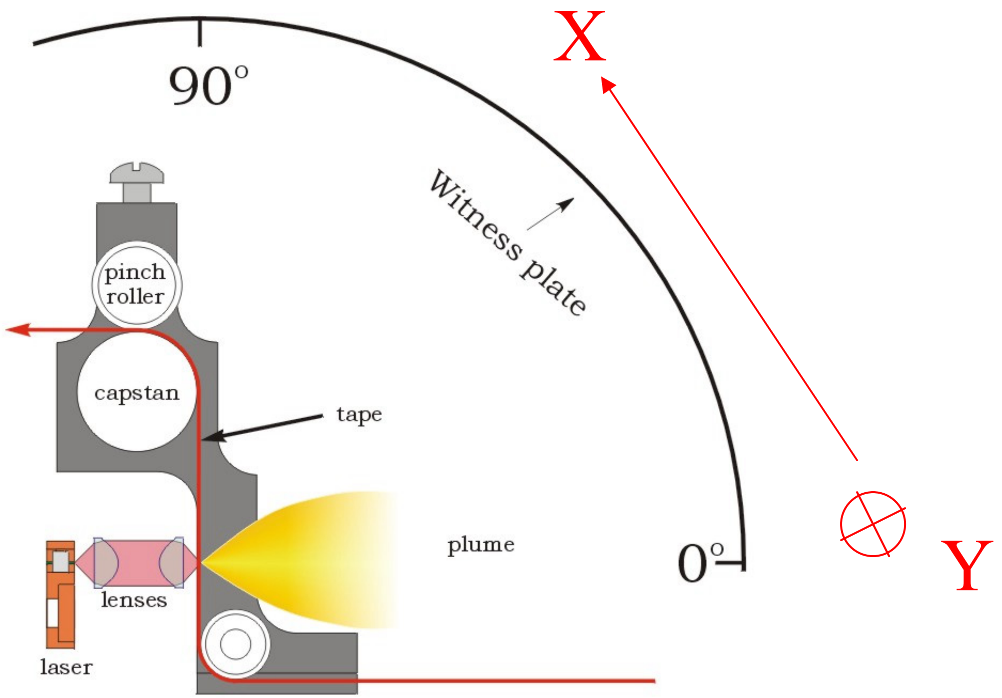
vacuum



8 W

Comparison with experiment (1)

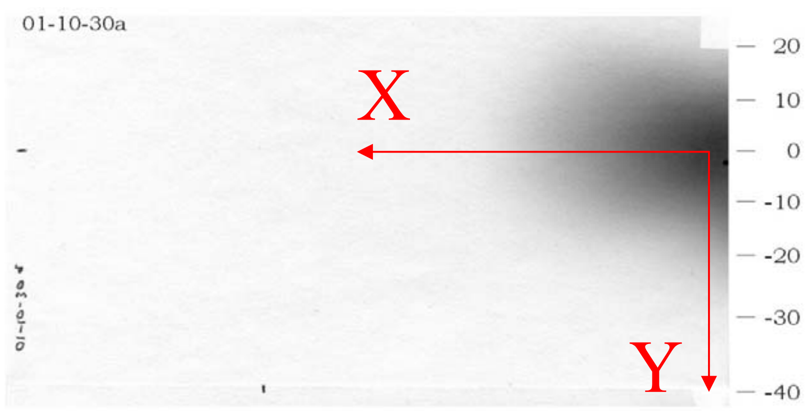
Experimental set up
Witness plate deposition

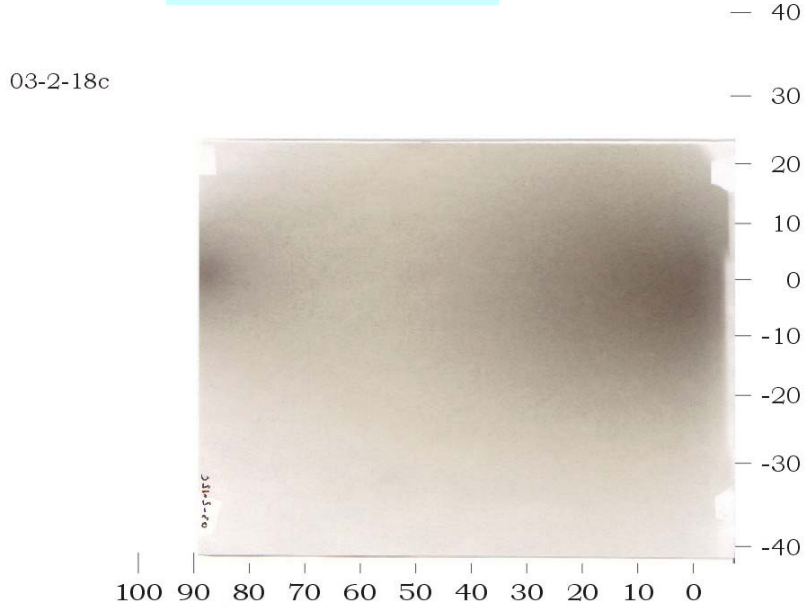


Comparison with experiment (2)

P=10^{-2} torr

P=6.5×10^{-5} torr



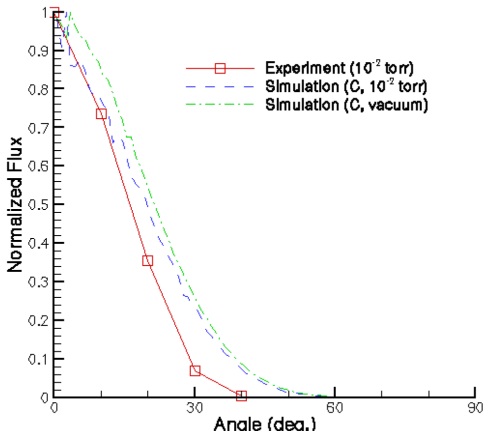


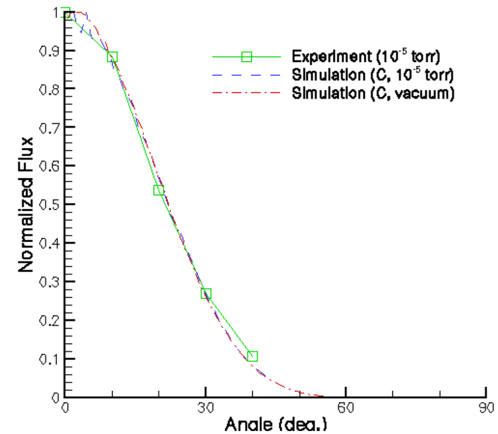
SEM analysis shows that deposition material is carbon
Thus carbon flux is compared with deposition profiles

Comparison with experiment (3)

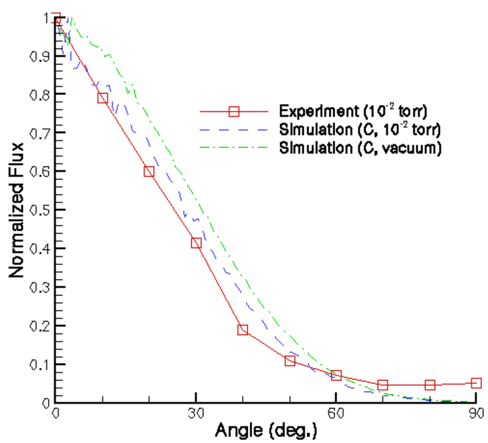
2.5 W; P=10^{-2} torr | **8 W; P=6.5×10^{-5} torr**

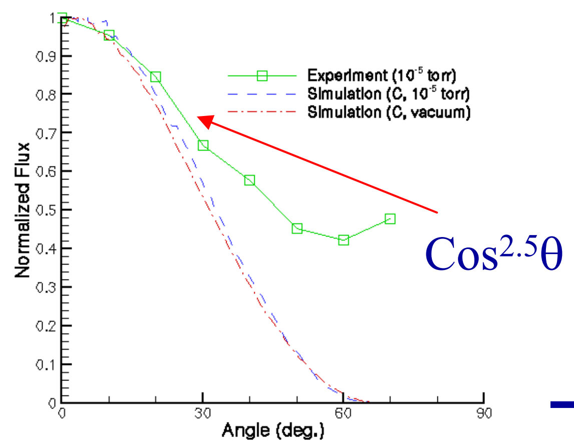
X





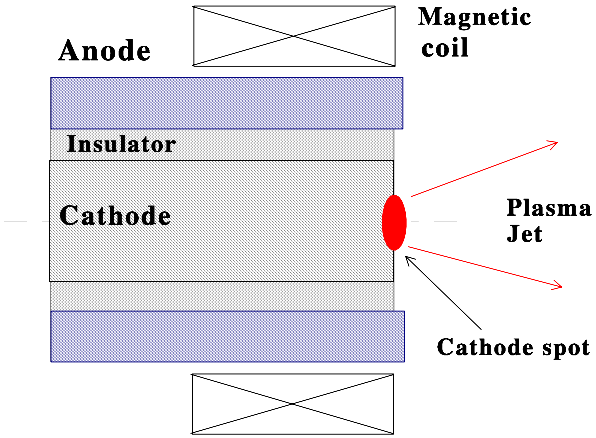
Y

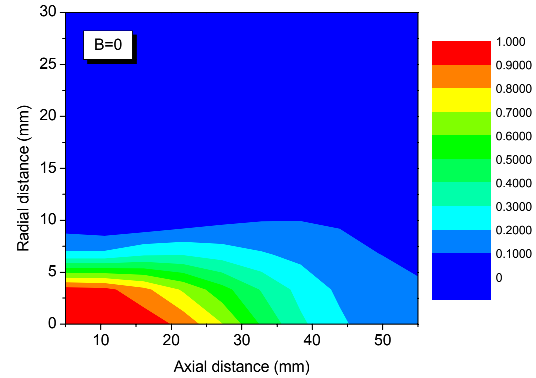


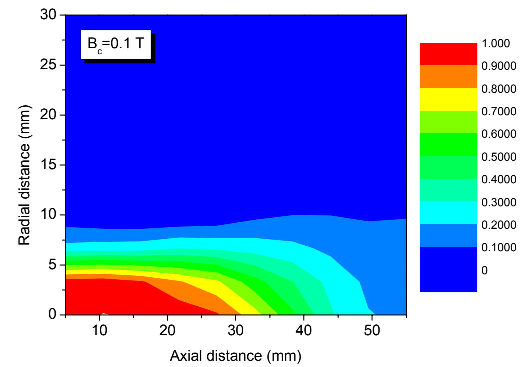


Background pressure and operational conditions

Micro-Vacuum Arc Thruster







MHD free boundary model

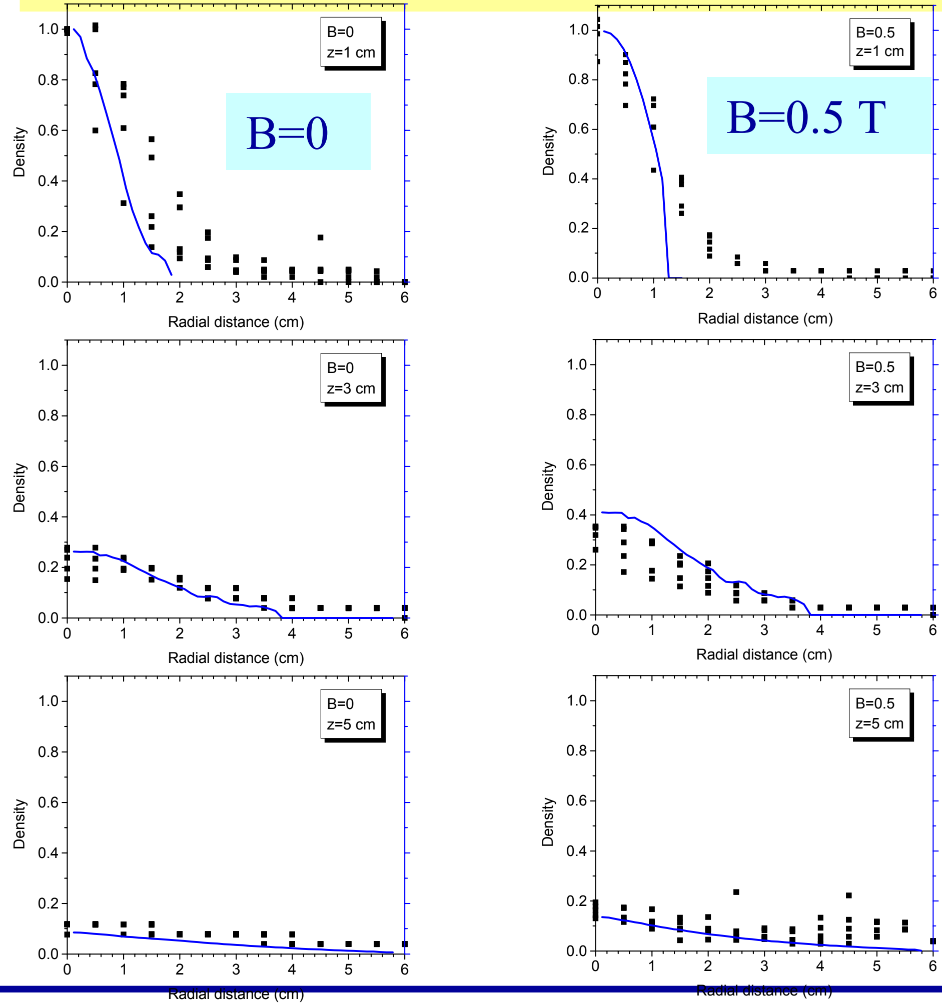
$$m_i (\mathbf{V}_i \cdot \nabla)\mathbf{V}_i = -k(Z_i T_e + T_i)\bullet\nabla \ln(n) + \mathbf{j}\times\mathbf{B}/n$$

$$\mathbf{j} = \sigma\{\mathbf{E} + (kT_e/e)\bullet\nabla \ln(n) - \mathbf{j}\times\mathbf{B}/(en) + (\mathbf{V}_i\times\mathbf{B})\}$$

$$\nabla\cdot(\mathbf{V}_i\, n) = 0$$

$$\nabla\cdot\mathbf{j} = 0$$

Micro-Vacuum Arc Thruster Plume



Summary (1)

– Various microthruster technologies based on ablative mechanism were developed

	μPPT	μVAT	μLPT
I_{sp}, s	1000	1000-3000	300-2000
I_{bit}, μN-s	1-10	1 [0.001-1]	0.001
T/P, μN/W	~10	2-20	50-100
Dry mass, kg	0.5	0.3	0.5
Flexibility	low	some	high
Experimental data	a lot	some	some
Modeling status	high	some	some

Summary (2)

– Self-consistent modeling approach for ablative micro-thrusters was formulated based on a kinetic ablation model and particle plume simulation.

– Most extensive validation of the modeling approach was performed for micro-pulsed plasma thruster. Plasma density, surface temperature, ablation rate, ablation profile were compared with experiment. Optimization criteria were formulated for some devices, such as microPPT.

Future needs

- Development of more flexible technology (variable I_{sp}, variable thrust)
  - μLPT pulse duration
  - μVAT pulse duration, material
- Contamination issues
  - Study is needed (μVAT)
- Lifetime issues (propellant recession)
  - μVAT, μPPT
- Hybrid thrusters
  - μVAT/μPPT; μLPT/μPPT
- Modeling: further characterization of thrusters (μVAT), plumes. Effect of the magnetic field